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PATENT

APPARATUS AND METHOD OF INFORMATION EXTRACTION FROM ELECTROMAGNETIC ENERGY BASED UPON MULTI-CHARACTERISTIC SPATIAL GEOMETRY PROCESSING

Related Applications

This application claims the benefit of U.S. Provisional Application No. 60/145,017, filed July 22, 1999, U.S. Provisional Application No. 60/145,194, filed July 23, 1999, and U.S. Provisional Application No. 60/145,264, filed July 26, 1999.

Field of the Invention

The present invention is directed to an apparatus and method that extracts and exploits information conveyed within spatial phase (e.g., three-dimensional geometry) characteristics of electromagnetic energy (e.g., light), and is particularly directed to an apparatus and method that extracts data from multi-characteristic spatial phase processing as a novel approach to providing information useful for imagery and the like.

Background of the Invention

Conventional imaging systems employ intensity-based techniques to handle electromagnetic energy proceeding from a source (e.g., an object). As one example of a conventional system, a spectroscopic system determines spectral (wavelength) composition of objects and scenes. The wavelengths that comprise the collected energy are separated with the use of a dispersive element employing refractive means, such as a prism, or diffractive means, such as a grating. After passing through one of these dispersive elements, the different wavelength components of the wave front propagate in different directions and the intensities of the components are recorded by an array of detector pixels. Such a standard spectrometer is an excellent device for determining the spectral composition of light emanating from a source object, but is unable to maintain two-dimensional spatial integrity of the source object. Typically, such a spectrometer is not capable of determining spectral content on a pixel-by-pixel basis, and merely collects the total intensity of electromagnetic energy proceeding from an object.

Fourier transform and Fabry-Perot interferometer systems are capable of performing imaging spectrometry

and determining the spectral composition of an object on a pixel-by-pixel basis. However, there are certain limitations imposed by the geometry of these systems. For example, in both types of systems, field of view of is severely restricted.

For the Fourier transform interferometer, the length of the system, combined with the small size of the mirrors, restricts the field of view because optical rays will not propagate through the system for large angles. Therefore, the number of pixels that can be acquired is limited.

For the Fabry-Perot interferometer, a small field of view is the result of two main effects. First, the light coming from the source object undergoes multiple reflections within a mirrored optical cavity before emerging from the system. When the incident light comes from an off-axis point on the object, it enters the cavity at an incident angle other than zero. Consequently, as the light undergoes multiple reflections, it will "walk" along the mirrors and eventually leak out of the cavity. The result of this behavior is that, as the field of view increases, the energy throughput of the system decreases.

The second problem that results in a limitation of the field of view for the Fabry-Perot system has to do with band pass variation with field size. Since the effective mirror separation changes with field angle, so does the filter band pass. To minimize the spectral variation from the center to the edge of the field, the field of view has to be small. However, this will again limit the number of pixels that can be obtained.

Still another problem that can arise with respect to some known systems, such as the Fourier transform interferometer, deals with image registration. Typically, two-dimensional images are acquired as one mirror is scanned. Problems associated with scanning, such as mirror jitter, uneven scanning, or mirror walking, create registration problems between the images in the different spectral bands.

In addition, many known systems employ scanning to acquire the spectral composition of the electromagnetic energy proceeding from a source object. During such scanning, it difficult to obtain the spectral composition in real-time while maintaining a high signal-to-noise ratio. This is not only a problem for the Fourier transform and Fabry-Perot interferometers, but also for electrically scanned systems such as

liquid crystal systems and acousto-optic tunable filter based imaging spectrometers, which have the additional problem of relatively low transmission.

Tomographic-based methods are sometimes used for imaging spectrometry tasks. Tomographic methods negate the need for scanning. However, the downside of this technique is that it is computationally intensive, requiring the mathematically determination of a system matrix, which is usually application specific.

As mentioned above, conventional imaging techniques employ intensity collection techniques. However, it is to be noted that, in distinction, spatial phase is intensity independent. Spatial phase characteristics of electromagnetic energy include characteristics of the plurality of polarizations (e.g., linear and circular) that are present within the electromagnetic energy.

As one type of utilization of polarization characteristics, polarimetry identifies, isolates, and/or uses a generalized polarization of electromagnetic energy. In the past, scientists have used polarimetry to filter imagery for specific applications. Polarization filters are used to collect polarization data, and classical polarization theory is

used to determine one level of the spatial phase properties. However, overall spatial phase of a propagated electromagnetic wave can a significant amount of information that is indicative of unique features about the wave history. For example, properties of an electromagnetic wave change as the wave interacts with media and changes as the wave transverses a surface.

In the past, scientists have attempted to build operational imaging polarimeters. None have been successful in providing an operation device that has abilities greater than a two channel orthogonal system. The polarimeters to date have been limited to a single set of four detectors or a rotating polarization analyzer. The rotating analyzer limits the system to static scenes and is not a useful tool for spatial phase analysis.

Another problem that arises for imaging systems that employ moving components, such as a rotating member, deals with the issue of image registration. However, problems associated with rotating, such as optical wedge wobbling, uneven rotating, or beam walking, create registration problems between the images in the different phase channels. With spatial

phase imaging, it is critical that each channel is identical in spatial content as well as angular information. Rotating systems will vary the angular extent of the object and cannot be used effectively.

Therefore, while some of the prior art is capable of performing limited polarimetry and other intensity-based applications, it is not capable, for the reasons discussed, of providing true, multi-dimensional, real-time spatial phase imaging.

The inventor has recognized that a spatial phase system would solve the above-mentioned problems and also go further into the complete analysis of the phase information, which is contained in the electromagnetic energy. By the scientific analysis of all the radiation being transmitted, reflected, emitted and/or absorbed, one can determine its phase properties. The phase properties are those characteristics that convey information (e.g., an indication of the media through which a wave has passed) that could allow significant imaging abilities. Along these lines, the inventor has recognized that spatial phase is a technology with tremendous benefit potential.

Summary of the Invention

In accordance with one aspect, the present invention provides an apparatus for information extraction from electromagnetic energy via multi-characteristic spatial geometry processing. Means receives electromagnetic energy from a source, the received electromagnetic energy has a plurality of spatial phase characteristics. Means separates the plurality of spatial phase characteristics of the received electromagnetic energy. Means identifies spatially segregated portions of each spatial phase characteristic, with each spatially segregated portion of each spatial phase characteristic corresponding to a spatially segregated portion of each of the other spatial phase characteristics in a group. Means quantifies each segregated portion to provide a spatial phase metric of each segregated portion for providing a data map of the spatial phase metric of each separated spatial phase characteristic.

In accordance with another aspect, the present invention provides an imaging apparatus that includes means for receiving electromagnetic energy proceeding from an object. Means creates an image of the object

utilizing only spatial phase characteristics of the electromagnetic energy proceeding from the object.

In accordance with another aspect, the present invention provides an imaging apparatus. Means receives electromagnetic energy proceeding from an object, wherein the electromagnetic energy conveying insufficient characterization in the visible and infrared spectrums to permit viable intensity-based and/or frequency-based image creation. Means creates an image of the object utilizing spatial phase characteristics of the electromagnetic energy proceeding from the object.

In accordance with yet another aspect, the present invention provides an imaging apparatus that includes means for receiving electromagnetic energy from an object. The received electromagnetic energy having a plurality of polarization characteristics. Means separates the plurality of polarization characteristics of the received electromagnetic energy. Means creates a plurality of images, each image being created using one of the separated polarization characteristics. Each image has a plurality of pixels, with each pixel of each image corresponding to a pixel of each of the other images in a group. Means quantifies a

polarization metric value at each pixel of each created image. Means determines an imaging value associated with each group of pixels using the quantified values. Means assembles an image using the determined imaging values.

In accordance with still another aspect, the present invention provides a method for information extraction from electromagnetic energy via multi-characteristic spatial geometry processing. Electromagnetic energy is received from a source. The received electromagnetic energy has a plurality of spatial phase characteristics. The plurality of spatial phase characteristics of the received electromagnetic energy are separated. Spatially segregating portions of each spatial phase characteristic are identified, with each spatially segregated portion of each spatial phase characteristic corresponding to a spatially segregated portion of each of the other spatial phase characteristics in a group. Each segregated portion is quantified to provide a spatial phase metric of each segregated portion for providing a data map of the spatial phase metric of each separated spatial phase characteristic.

In accordance with yet still another aspect, the present invention provides a method of creating an image. Electromagnetic energy proceeding from an object is received. An image of the object is created utilizing only spatial phase characteristics of the electromagnetic energy proceeding from the object.

Brief Description of the Drawings

The foregoing and other features and advantages of the present invention will become apparent to those skilled in the art to which the present invention relates upon reading the following description with reference to the accompanying drawings, in which:

Fig. 1 is an example schematic block diagram of an system in accordance with one aspect of the present invention, the system is an imaging system utilizing separated electromagnetic spatial phase characteristics for image creation;

Fig. 2 is an illustration of an example embodiment of an optical system, in accordance with another aspect of the present invention, that may be used to provide the function of separating a plurality of spatial phase characteristics for provision to a plurality of detector arrays of the imaging system of Fig. 1;

Figs. 3A-3D are graphical representations of the spatial phase characteristics that are separated by the optical system of Fig. 2;

Figs. 4A-4D are schematic representations of detector arrays of the system of Fig. 1, and have example representation spatial phase metric values shown for a pixel group;

Fig. 5 is an illustration of an object having a plurality of distinct surfaces;

Fig. 6 is an image of the object of Fig. 5 provided via thermal imaging when a temperature gradient between the surfaces does not exist;

Fig. 7 is an image of the object of Fig. 5 provided by the system of Fig. 1 and in accordance with the present invention under the same temperature conditions as the image created for Fig. 6;

Fig. 8 is a representation of an image of an object, with expanded portions that indicate spatial phase differences between the portions;

Fig. 9 is a plot indicating contrast during temperature difference change for infrared intensity and polarization phase, as a spatial phase characteristic;

Fig. 10 is a plot indicating contrast over a range of distances from an imaging system for infrared intensity and polarization phase, as a spatial phase characteristic;

Fig. 11 is a illustration showing scattering of a bulk of electromagnetic energy proceeding from an object with a minimal amount of the energy reaching the system of Fig. 1;

Fig. 12 is a generalized image-creation embodiment showing another approach to separation of electromagnetic spatial phase characteristics from an object;

Fig. 13 is an example embodiment of an optical system used to separate electromagnetic energy for detector arrays in accordance the approach of Fig. 12;

Fig. 14 is a generalized image-creation embodiment showing another approach to separation of electromagnetic spatial phase characteristics from an object; and

Fig. 15 is a plot indicating examples of spatial phase characteristic.

Description of Exemplary Embodiments

An example of one type of information discerning and utilizing system 10 in accordance with the present

invention is schematically shown in Fig. 1. In the illustrated example, the system 10 is an imaging system. For example, the system may be a camera arrangement. However, it is to be understood that the present invention is not limited to an imaging system. For example, the present invention can be utilized to provide data transfer, identification, recognition, etc.

The imaging system 10 provides a real-time image of an object 2 on a display 12, utilizing multi-characteristic spatial geometric attributes within electromagnetic energy 4 proceeding from the object. Specifically, the three-dimensional elliptical shape of an electromagnetic wave as it sweeps through space provides a multitude of information.

It is to be appreciated that electromagnetic energy is indented to encompass any and all wave energy in the spectrum of electromagnetic energy. Examples of electromagnetic energy include the visible light range, the infrared range, the ultraviolet range, the microwave range, the x-ray range, the gamma ray range, and the radio frequency range. For simplicity, the examples presented herein are discussed primarily with regard to the portion of the electromagnetic spectrum

that is at or near the visible, infrared and/or ultraviolet ranges.

Also, the image provided on the display 12 has an appearance dependent upon the operation of the system 10. For example, the image may provide a three-dimensional representation of the object 2, a contrast representation of the object, a surface orientation/curvature representation of the object, a material composition representation of the object, or a low light level image (shadow penetration) of the object. These imaging feature abilities may be provided by the example embodiments described in more detail below.

In the illustrated example of Fig. 1, an electromagnetic energy-handling portion 6 receives and handles the electromagnetic energy 4 proceeding from the object 2. For the portion of the electromagnetic spectrum that is at or near the visible, infrared and/or ultraviolet ranges the electromagnetic energy-handling portion 6 typically includes optical elements. However, it is to be appreciated that the electromagnetic energy handling portion 6 will include components appropriate to receive and handle the portion of the electromagnetic spectrum that is to be

utilized. For example, the electromagnetic energy-handling portion 6 may include one or more antennas or other receiving structures.

The electromagnetic energy-handling portion 6 specifically includes a plurality of spatial phase separating/isolating/distinguishing components 8A-8X. Each component (e.g., 8A) functions to separate/isolate/distinguish at least one certain, distinct spatial phase attribute or characteristic (e.g., 9A, a polarization characteristic) of the electromagnetic energy 4. The separation/isolation/distinction preferably includes spatial slicing of the electromagnetic wave 4. It is to be appreciated that the components 8A-8X may comprise any suitable structure appropriate to accomplish the separating/isolating/distinguishing function. Examples of structures include filters (e.g., polarization), small diffraction gratings, wires or the like, optical elements employing surfaces at predetermined orientations (e.g., Brewster's angle), and antenna arrays. Preferably, different spatial phase attributes or characteristics are separated/isolated/distinguished via each component (e.g., 8A). In sum, each component (e.g., 8A) provides

a version or representation of an image of the object, as perceived in the realm of the distinct spatial phase attribute(s) or characteristic(s) associated with that component.

A plurality of detector arrays 14A-14X is provided within the imaging system 10 and is associated with the plurality of separating/isolating/distinguishing components 8A-8X. Each detector array (e.g., 14A) detects electromagnetic energy having a certain spatial phase attribute or characteristic. Examples of detector arrays include CCD and FPA.

Preferably, each detector array (e.g., 14A) detects the certain spatial phase attribute or characteristic associated with an associated separating/isolating/distinguishing component (e.g., 8A). Each detector array (e.g., 14A) has a plurality of spatially segregated locations (e.g., pixels) at which a spatial phase metric value is quantified. It is to be appreciated that although the example embodiment has plural detector arrays, the same function could be accomplished via division of a lesser number (e.g., one) of detector arrays into a plurality of portions (e.g., sub-arrays of pixels). Also, it is

to be appreciated that the division may even be at the singular pixel level.

The spatial phase metric is a value of the spatial phase characteristic at that pixel for the spatial phase characteristic associated with that particular detector array (e.g., 14A) or detector array portion. In the illustrated example, each detector array (e.g., 14A) is an N by M array. Accordingly, the spatial phase metrics provide an N by M map of the characteristic. Further, it is to be appreciated that all of the detector arrays 14A-14X, or detector array portions, are related such that each spatially separated point (e.g., pixel) at each detector array (e.g., 14A), or detector array portion, is related in a group to a corresponding spatially separated point (e.g., pixel) within each of the other detector arrays (e.g., 14B-14X), or detector array portions. Thus, different N by M maps are provided for the different characteristics.

Suitable means 16A-16X are operatively connected 18A-18X for holding/passing the determined spatial phase metric values associated with the plurality of the pixels of the detector array 14A-14X. In the illustrated example, such a function is provided by a

buffer memory (e.g., 16A) that is operatively (e.g., 18A) connected to a respective detector array (e.g., 14A).

The plurality of buffer memories 16A-16X is operatively connected 20A-20X to a processor 24. In the illustrated example of Fig. 1, the processor 24 is a single processor. However, it is to be appreciated that compound or parallel processors may be employed. In general, the processor 24 determines an imaging value for each group of pixels that correspond among the detector arrays 14A-14X. The imaging value is utilized to provide a portion of the image that is provided on the display 12. The imaging values that are determined by the processor 24 are provided to the display 12 by any suitable means 26. In the illustrated example of Fig. 1, the means 26 is shown as a buffer memory 26 that is operatively connected 28 and 30 to the processor 24 and the display 12, respectively. The buffer memory 26 holds/passes point characterizations of an M by N matrix of the display 12.

Focusing on the operation of the processor 24, the processor determines the imaging value for each pixel by mathematical processes that are performed upon the

spatial phase metric values of each associated group of pixels. The processing differs dependent upon the polarization characteristics that are received at each of the detector arrays 14A-14X. The processing also differs dependent upon the number of detector arrays 14A-14X that are included within the imaging system 10. Regardless of these variable aspects, the processing is based upon the realization that spatial phase characteristics that are present within electromagnetic energy retain information (e.g., a history of the origin and propagation of the electromagnetic wave). The electromagnetic wave has a unique signature that is exploited by separation for the plurality of detector arrays 14A-14X, the spatially-separated (e.g., pixel) detection at the detector arrays, and the processing within the processor 24. Accordingly, any suitable equation base, such as a stoke-equation base, may be utilized to process spatially-separated spatial phase metric values. Thus, spatial phase characteristic metric values, provided via the detector arrays 18A-18X, are used to create the image.

Also, it is to be appreciated that the processing may include first-level processing that generates

spatial phase characteristic metric values using the spatial phase metric values that are provided via the detector arrays 18A-18X. Each particular type of generated spatial phase characteristic metric value may be provided in a complementary size matrix. The generated spatial phase characteristic metric values, with or without the spatial phase characteristic metric values provided via the detector arrays 18A-18X, are then used to create the image. For example, the spatial phase characteristic metric values provided via the detector arrays 18A-18X may include polarization characteristics (e.g., orientation and degree). The generated spatial phase characteristic metric values may represent shape, material, index of refraction, slope, three-dimensionality, polarization computation, phase geometry, object geometry, or molecular composition.

Turning to the separation of electromagnetic energy into different characteristic separation components 8A-8X, and the spatial phase characteristics that are separated, it is to be appreciated that various physical embodiments may be utilized to separate the spatial phase characteristics. The embodiments may differ dependent upon the number of

separations desired and the separations that are accomplished. It is to be appreciated that the desired type and number of separations is related to the number and type of detector arrays 14A-14X, and more importantly the type of processing that occurs within the processor 24.

It is to be appreciated that the imaging system 10, with or without the shown electromagnetic handling portion 6, is considered an imaging apparatus. The distinction only goes to separation state of received electromagnetic energy. For example, the shown electromagnetic handling portion 6 would not be necessary if the electromagnetic energy is provided to the detector arrays 14-14X is a pre-separated/isolated/distinguished format. However, for ease of understanding, the disclosed examples include the separating/isolating/distinguishing feature.

Accordingly, Fig. 2 illustrates an example of one optical arrangement 100 that provides the function (i.e., provide separated spatial phase characteristics) of the electromagnetic energy handling portion 6 of the imaging system 10 of Fig. 1. Specifically, the separated spatial phase characteristics include polarization characteristics. However, it is to be

appreciated that the example of Fig. 2 is not a limitation of the subject invention, but is merely one embodiment of the electromagnetic energy-handling portion 6.

The optical system 100 is utilized within an embodiment of the imaging system 10 that has four detector arrays (i.e., 14A-14D). Also, in the example of Fig. 2, the source object 2 that is to be imaged is a physical object 102. Fig. 2 illustrates the object 102 in a schematic (i.e., block) configuration. It is to be appreciated that the object 102 may take any form.

Electromagnetic energy (e.g., light) 104 that proceeds from the object 102 is received at a first optic arrangement 106, which is preferably is a multi-element, sequential lens arrangement. The electromagnetic energy 108 that proceeds from the first optic arrangement 106 is focused at a field stop 110 and proceeds to a second optic arrangement 112. Preferably, the second optic arrangement 112 is a multi-element, sequential lens arrangement. The second optic arrangement 112 collimates the electromagnetic energy into a beam 114. It should be appreciated that the cross-section of the electromagnetic beam 114 is

representative of electromagnetic energy from the entire object 102.

A pyramid prism 116 is located such that the beam 114 impinges upon each of four prism faces (only two faces 120A and 120B shown for simplicity). Specifically, the prism 116 is at a pupil plane that is oriented perpendicular to the beam. Associated with each of the prism faces (e.g., 120A and 120B) is a reflecting surface (only two shown, e.g., 124A and 124B). Reflected beams (only two shown, e.g., 126A and 126B) that proceed from the reflecting surfaces (e.g., 124A and 124B) impinge on respective phase/polarization filters (only two of the four filters shown for simplicity, e.g., 130A and 130B). Accordingly, in the example of Fig. 2, the pupil plane is split or separated into a plurality (i.e., four) parts.

Each phase/polarization filter (e.g., 130A) permits passage of only a certain polarization characteristic of the electromagnetic energy. For example, the first phase/polarization filter 130A passes only linear polarization at a zero degree phase. Such a polarization characteristic is illustrated by the graphic of 3A. The second phase/polarization

filter 130B passes only linear polarization at a 45° phase. Such a polarization characteristic is illustrated by the graphic of Fig. 3B. The third phase/polarization filter passes only linear polarization at a 90° phase. Such a polarization characteristic is illustrated by the graphic of Fig. 3C. The fourth phase/polarization filter passes only circular (e.g., left-hand/right-hand) polarization. Such a polarization characteristic is illustrated by the graphic of Fig. 3D. Accordingly, in the example of Fig. 2, the four parts from the pupil plane are each filtered in a different manner to create four different characteristic conveying beams (e.g., 134A and 134B), wherein each beam has a different "slice" of the overall spatial properties of the electromagnetic energy 104.

Turning again to Fig. 2, a third optic arrangement 132 is provided for focusing electromagnetic energy (e.g., 134A and 134B) as a plurality of images for the plurality of detector arrays 14A-14D. Specifically, the third optic arrangement 132 focuses the electromagnetic energy proceeding from the first reflecting surface 124A that passes through the first phase/polarization filter 130A

onto the first detector array 14A. Similarly, the third optic arrangement 132 focuses the electromagnetic energy that proceeds from the second reflecting surface 124B that passes through the second phase/polarization filter 130B onto the second detector array 14B. Similar focusing occurs for the third and fourth detector arrays. Preferably, the third optic arrangement 132 is a multi-element, sequential lens arrangement. One important feature that is associated with the embodiment of Fig. 2 is that the optical elements are non-moving.

It should appreciated that the focusing of the images onto the detector arrays 14A-14D is such that there is a point-by-point (e.g., pixel-by-pixel) correspondence between all of the detector arrays. In other words, each certain pixel position at each detector array (e.g., 14A) corresponds to an identical certain pixel position at all of the other detector arrays (e.g., 14B-14D). Thus, the dissected polarization characteristics for each pixel can be processed within the processor 24 (Fig. 1).

Such a correspondence of the dissected polarization characteristics is shown by the representations of Figs. 4A-4D. Specifically, a

pixel 140A location on the first detector array 14A has a certain polarization metric value that is represented by certain shading within Fig. 4A. It is to be appreciated that the polarization metric value for the polarization characteristic (e.g., linear polarization at zero phase) has a value that is dependent upon the image as provided to the first detector array 14A for the certain polarization characteristic. The Figs. 4B-4D have similar graphical shading representations for pixels 140B-140D, respectively, to indicate polarization metric values of their associated polarization characteristics (e.g., linear polarization at 45° in Fig 4B, linear polarization at 90° in Fig. 4C, and circular polarization in Fig. 4D).

Again, turning to the imaging system 10 of Fig. 1, the processor 24 utilized the mapping created by the separation. Specifically, the processor 24 performs the mathematical process on the polarization metric values within the group for each pixel location to provide an image value that will be displayed to create the image at the display 12 for the certain pixel location.

Turning to the benefits associated with an imaging apparatus in accordance with the present invention, an

image created utilizing polarization characteristics is not subject to the limitations associated with various known imaging techniques. To illustrate, attention is directed to Fig. 5, which shows a three-dimensional object 150. For simplicity, the object 150 is shown as a cube. In Fig. 5, the cube 150 is oriented such that three surfaces 152, 154, and 156 are presented. Edges 160-164 separate the three presented surfaces 152-156.

Now, assume that the cube 150 is at an ambient temperature and does not have any temperature gradient between any portion (e.g., the surfaces 152-156). Conventional infrared imaging of the cube 150 produces an image 168 as shown in Fig. 6. Specifically, so long as the cube 150 is at a thermal gradient to its background, the cube is distinguishable, but because of the lack of a thermal gradient between the portions of the cube, only an outline of the cube is discerned.

When the cube 150 of Fig. 5 is imaged with the imaging apparatus in accordance with the present invention, an image 170 (Fig. 7) would be provided on the display 12. Specifically, the image 170 clearly shows three distinct surface representations 172-176 separated by three distinct edge representations

180-184. Again, the ability of the imaging system 10 to provide the image 170 is based upon the fact that the polarization of the electromagnetic energy proceeding from each of the three surfaces 152-156 of the cube 150 of Fig. 5 has some difference in polarization characteristics.

It is not so important as to what the differences in the polarization characteristics are, but it is that a difference exists which permits the image 170 to be created. This concept is illustrated by the representation of an image of a two dimensional object shown by Fig. 8. The image of the object (represented merely by the text "image") is comprised of pixels that each are associated with a different spatial phase identification. In the example of Fig. 8, three pixels are selected to stand out, and a graphical representation indicating spatial phase identification is provided for each pixel. It is to be noted that the different pixels have different spatial phase identifications.

The ability to create an image that has discernable detail is related to the amount of polarization contrast, whatever the contrast may be, that can be discerned to create the image. Fig. 9

illustrates contrast that may be discerned for image creation in both an infrared intensity that is known in the prior art, and a polarization phase analysis in accordance with the present invention. Specifically, at a very large temperature difference, either cold or hot, from a reference point, infrared intensity will provide suitable contrast to permit an image to be created using an infrared technique. However, when a temperature difference does not exist, an image with viable resolution cannot be created using infrared intensity. In contrast, polarization-phase imagery remains at a relatively high contrast regardless of temperature gradient.

Other benefits to polarization phase imagery exist. For example, for an intensity-based imaging system to provide a usable image, sufficient intensity must be supplied to the imaging system. However, intensity decreases as a square of the inverse of the distance between an object and an imaging system. Thus, as shown in Fig. 10, at a relatively close range, an infrared intensity imaging system would provide for relatively high contrast. However, at increased distances, the intensity would decrease to the point that contrast is insufficient for imaging purposes. In

distinction, a polarization phase-based image can be generated because polarization characteristics do not decrease, or decrease little in relationship to distance. Thus, so long as some electromagnetic energy is received at the imaging system 10 of Fig. 1, a polarization-based image can be created.

It should be further realized that, in view of the fact that only a certain minimal amount of electromagnetic energy is necessary for the creation of a polarization phase-based image, a relatively large amount of electromagnetic energy that proceeds from an object may be lost or unused without effecting the ability of the system to provide an image. For example, as shown in Fig. 11, an object 190 emits electromagnetic energy 192. A dense scattering media 194 is located between the object and the imaging system 10 and its associated optical system 100. The dense scattering media 194 causes a scattering (e.g., random dispersion) 196 of the electromagnetic energy.

Some electromagnetic energy 198 proceeds from the dense scattering media 194 to the optical system 100 and thus to the imaging system 10. This electromagnetic energy 198 will provide sufficient

information within its polarization characterization to permit an image to be provided of the object 190.

It is to be appreciated that the dense scattering media 194 may alter polarization characteristics. This is due to the fact that polarization characteristics retain a complete history. However, it is to be appreciated that sufficient information contained in the polarization characteristics to permit the image of the object 190 to be created.

Fig. 12 illustrates another approach to separation of electromagnetic spatial phase characteristics from an object 260. Electromagnetic energy 262 proceeding from the object 260 is provided to a plurality of isolation components 264-272. The isolation components 264-272 operate to provide certain spatial phase characteristics 274-282 (e.g., slices of the spatial phase of the electromagnetic energy 262). The characteristics 274 are near pure such that the portions 284-292 of the image associated with the respective characteristic are completely separate. Thus, each map created is for a purely distinct spatial phase characteristic.

This complete separation or isolation is accomplished by each isolation component (e.g., 264)

operating effectively at 100% efficiency to strip out all spatial phase characteristics except for the desired spatial phase characteristic. As with the other embodiments, the separated characteristics are processed and used (represented schematically by the traces 294) to create an image 296.

Fig. 13 illustrates an example embodiment of an optical system 200 that is utilized to provide separated spatial phase (e.g., polarization) characteristics in accordance with the approach shown in Fig. 12. Of course, it is to be appreciated that although the example of Fig. 13 is an optical system, the approach of Fig. 12 is not so limited. Similar to the embodiment shown in Fig. 2, the elements of the embodiment of Fig. 13 do not move (e.g., non-scanning).

The optical system 200 is utilized within an embodiment of an imaging system (e.g., similar to the imaging system 10 of Fig. 1) that has four detector arrays (i.e., 14A-14D). In the example of Fig. 13, the source object that is to be imaged is a physical object 202.

Electromagnetic energy (e.g., light) 204 that proceeds from the object 202 is received at a first optic arrangement 206, which is preferably is a multi-

element, sequential lens arrangement. The electromagnetic energy 208 that proceeds from the first optic arrangement 206 is focused at a field stop 210 and proceeds to a second optic arrangement 212. Preferably, the second optic arrangement 212 is a multi-element, sequential lens arrangement. The second optic arrangement 212 collimates the electromagnetic energy into a beam 214. It should be appreciated that the cross-section of the electromagnetic beam 214 is representative of electromagnetic energy from the entire object 202.

A first interference filter 216 is located in the path of the beam 214. The first interference filter 216 reflects certain polarization characteristic(s) and passes certain polarization characteristic(s) of the electromagnetic energy. The reflected electromagnetic energy provides a beam 218, and the passed electromagnetic energy impinges upon a first reflecting surface 222. A beam 224 extends from the first reflecting surface 222. The first interference filter 216 and the first reflecting surface 222 are at different orientations (e.g., different angles). Thus, the beam 218 and the beam 224 proceed along different paths.

A second reflecting surface 230 and a second interference filter 232 receive the beams 218 and 224. Again, because of the properties of the second interference filter, the electromagnetic energy is further separated based upon polarization properties. Also, because of a difference in orientation of the second reflecting surface 230 and the second interference filter 232 the separated electromagnetic energy is directed along different paths. The result of the separations is four beams (only two shown, e.g., 236A and 236B), with polarization characteristic distinction for each beam.

A third optic arrangement 240 is provided for focusing the electromagnetic energy (e.g., 242A and 242B) as a plurality of images for the plurality of detector arrays 14A-14D. Preferably, the third optic arrangement 132 is a multi-element, sequential lens arrangement. It should appreciated that the focusing of the images onto the detector arrays 14A-14D is such that there is a point-by-point (e.g., pixel-by-pixel) correspondence between all of the detector arrays. In other words, each certain pixel position at each detector array (e.g., 14A) corresponds to an identical certain pixel position at all of the other detector

arrays (e.g., 14B-14D). Thus, the dissected polarization characteristics for each pixel can be processed within the processor 24 (Fig. 1).

Fig. 14 illustrates another approach to separation of electromagnetic spatial phase characteristics from an object 302. Electromagnetic energy proceeding from the object 302 is focus by a lens arrangement 304 onto a detector array 306. The detector array 306 has a plurality of discrete locations (e.g., pixels). Each location or pixel collects and stores spatial phase characteristics (e.g., slices of the spatial phase of the electromagnetic energy). The spatial phase identification of the electromagnetic energy at each location is the stores in a matrix 310 (the identification of the electromagnetic energy at each location is represented by a graphical symbol). Thus, the matrix 310 is the map. Further processing can then be accomplished via various used of location-by-location (e.g., pixel-by-pixel) analysis. For example, gradients between adjacent locations (pixels) are analyzed, a series of locations (pixels) are analyzed for curvature. Also, each row or column can be considered to be a slice of the electromagnetic energy. Accordingly, slicing of the electromagnetic energy to

derive information can be accomplished in different ways.

Fig. 15 is a graphical example that illustrates spatial phase characteristics that may be associated with a single location (e.g., pixel) in the example of Fig. 14 (or in some of the other above-described examples). In the example, the characteristics are separated by identifiers that are also referred to as bins. Further, the bins include polarization characteristics (e.g., the first four bins), angle, and material.

Some possibilities for the present invention include reconstruction of surface geometry (3-D) via constant phase contrast (which is typically constant for polarization), penetration of shadows via amplitude-independent (intensity-independent) processing, detection through scattering media. It is contemplated that spatial phase could be used in conjunction with any system to add discrimination ability. For example, spatial phase technology accordingly to the present invention can be effectively added to any sensor to expand that sensor capability to include phase information. Further, imaging data derived via the spatial phase technology accordingly to

the present invention can be merged or fused with imaging data derived via other methods (e.g., regular imaging, infrared imaging) to provide an enhanced image.

Specific applications for the subject invention are numerous. Some applications are is the medical field (non-invasive glucose, ocular analysis for disease, etc., cancer (e.g., skin, breast, cervical, prostrate) diagnosis, and identification of DNA taggents and blood analytes. Other applications are to be found in industry, such as non-destructive inspections, 3-D profiling, telecommunications, remote sensing, and process control. For example, crystal growth can be monitored in real-time to immediately provide information regarding imperfections. Licensed government use could include weapons testing, and enemy detection and observation.

Still further, the three dimensional imaging ability that the present invention provides lends itself to a myriad of possibilities such as real-time contour display of a map or the like. The spatial phase ability of the present invention is also useful for feature extraction and classification. Such specific application could entail pattern recognition,

image enhancement, and scene analysis. For example, movement of objects, people, or the like can be monitored via the use of a spatial-phase identification marker or tag.

As a specific example, the present invention is usable to identify specific items that are marked with predefined tags. Each tag provides for at least one certain spatial phase characteristic within the electromagnetic energy proceeding from the tag. The certain spatial phase characteristic is identifiable, and thus the tag provided on the item is identifiable. The item may be any item, such as a person, and the tag may have any suitable construction.

Still further, because the electromagnetic energy may be at any portion of the spectrum, the applications may utilize any medium of electromagnetic conveyance to an apparatus in accordance with the present invention. For example, air/space (e.g., wireless), wire, fiber optic cable, storage media, and the like are all suitable conveyance mediums.

From the above description of the invention, those skilled in the art will perceive improvements, changes and modifications. Such improvements, changes and

modifications within the skill of the art are intended to be covered by the appended claims.